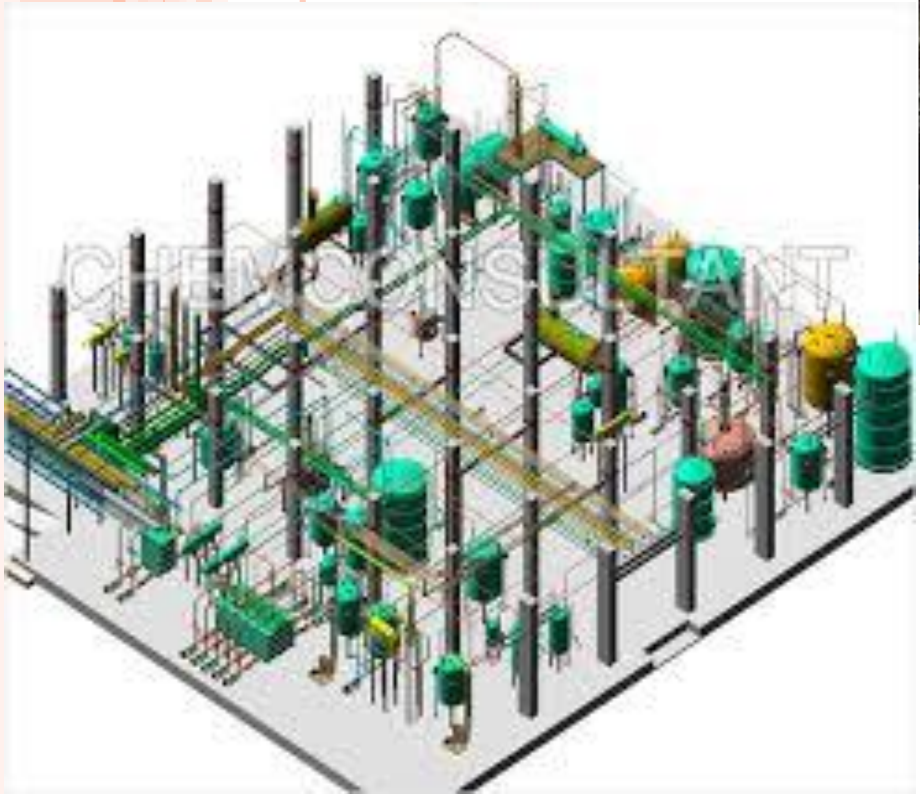
BIOPROCESS EQUIPMENT DESIGN



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Cyclone separator

Cyclone separator

GAS-SOLIDS SEPARATIONS (GAS CLEANING)

The primary need for gas-solid separation processes is for gas cleaning: the removal of dispersed finely divided solids (dust) and liquid mists from gas streams. Process gas streams must often be cleaned up to prevent contamination of catalysts or products, and to avoid damage to equipment, such as compressors. Also, effluent gas streams must be cleaned to comply with air-pollution regulations and for reasons of hygiene, to remove toxic and other hazardous materials.

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There is also often a need for clean, filtered, air for process using air as a raw material, and where clean working atmospheres are needed: for instance, in the Food and pharmaceutical, Chemical and petrochemical industries….etc

The particles to be removed may range in size from large molecules, measuring a few hundredths of a micrometer, to the coarse dusts arising from the attrition of catalysts or the fly ash from the combustion of pulverized fuels.

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A variety of equipment has been developed for gas cleaning. The principal types used in the process industries are listed in Table below, it shows the general field of application of each type in terms of the particle size separated, the expected separation efficiency, and the throughput. It can be used to make a preliminary selection of the type of equipment likely to be suitable for a particular application. Descriptions of the equipment shown in Table 1 can be found in various handbooks: Perry and Green (1984), Schweitzer (1988); and in several specialist texts: Nonhebel (1972), Strauss (1966), Dorman (1974), Rose and Wood (1966),

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Table 1 gas cleaning equipment's

Type of equipment	Minimum particle size (μm)	Minimum loading (mg/m^3)	Approx. efficiency (%)	Typical gas velocity (m/s)	Maximum capacity (m^3/s)	Gas pressure drop (mm H_2O)	Liquid rate ($m^3/10^3$ m^3 gas)	Space required (relative)
Dry collectors								
Settling chamber	50	12,000	50	1.5–3	none	5	—	Large
Baffle chamber	50	12,000	50	5–10	none	3–12	—	Medium
Louver	20	2500	80	10–20	15	10–50	—	Small
Cyclone	10	2500	85	10–20	25	10–70	—	Medium
Multiple cyclone	5	2500	95	10–20	100	50–150	—	Small
Impingement	10	2500	90	15–30	none	25–50	—	Small
Wet scrubbers								
Gravity spray	10	2500	70	0.5–1	50	25	0.05–0.3	Medium
Centrifugal	5	2500	90	10–20	50	50–150	0.1–1.0	Medium
Impingement	5	2500	95	15–30	50	50–200	0.1–0.7	Medium
Packed	5	250	90	0.5–1	25	25–250	0.7–2.0	Medium
Jet	0.5 to 5 (range)	250	90	10–100	50	none	7–14	Small
Venturi	0.5	250	99	50–200	50	250–750	0.4–1.4	Small
Others								
Fabric filters	0.2	250	99	0.01–0.1	100	50–150	—	Large
Electrostatic precipitators	2	250	99	5–30	1000	5–25	—	Large

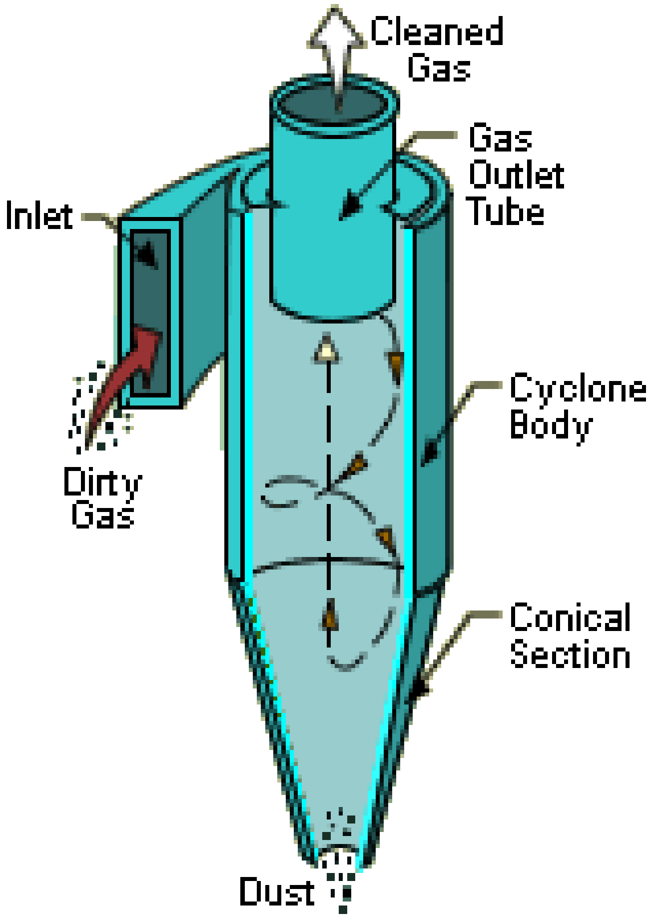
Cyclone separator

Cyclone separators are the principal type of gas-solids separator employing centrifugal force, and are widely used. They are basically simple constructions; can be made from a wide range of materials; and can be designed for high temperature and pressure operation.

Cyclones are suitable for separating particles above about 5 µm diameter; smaller particles, down to about 0.5 µm can be separated by filters.

Cyclone separator

Reverse-flow cyclone are commonly used for gas solid separator. In a reverse-flow cyclone the gas enters the top chamber tangentially and spirals down to the apex of the conical section; it then moves upward in a second, smaller diameter, spiral, and exits at the top through a central vertical pipe. The solids move radially to the walls, slide down the walls, and are collected at the bottom.



Cyclone separator

Advantages of cyclones:

- Low capital cost (few parts, easy to assemble)
- Ability to operate at high temperatures (all metal parts)
- Low maintenance requirements (no moving parts).

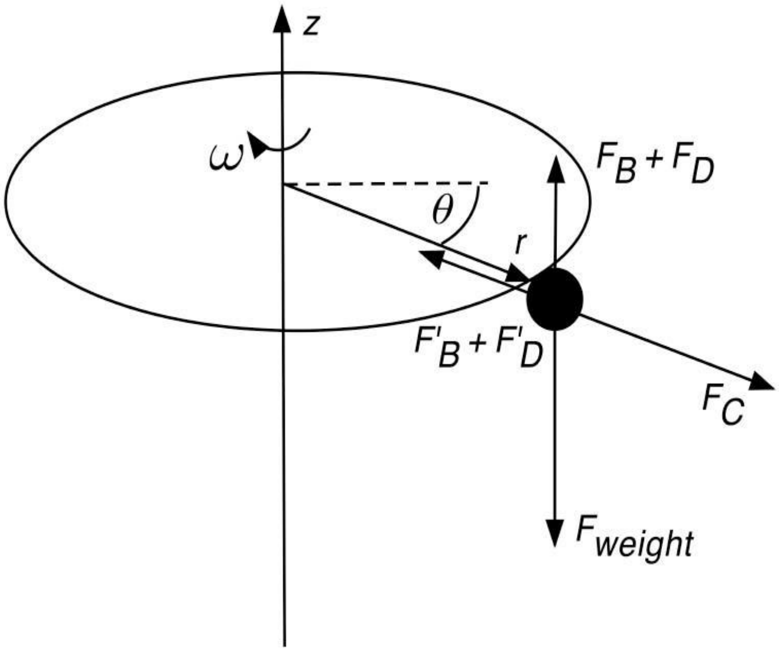
Disadvantages of cyclones:

- Low collection efficiencies (especially for very small particles)
- Cyclones used almost exclusively for particles > 5 µm.

Cyclone separator

Velocity distribution inside the Cyclone

- Axial velocity
- Radial velocity
- Tangential velocity



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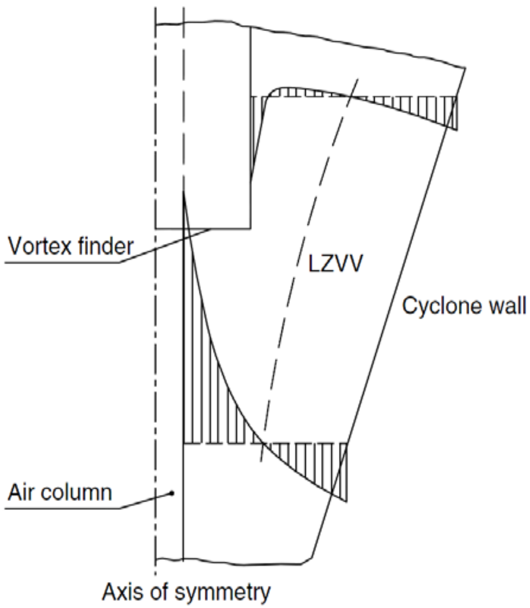
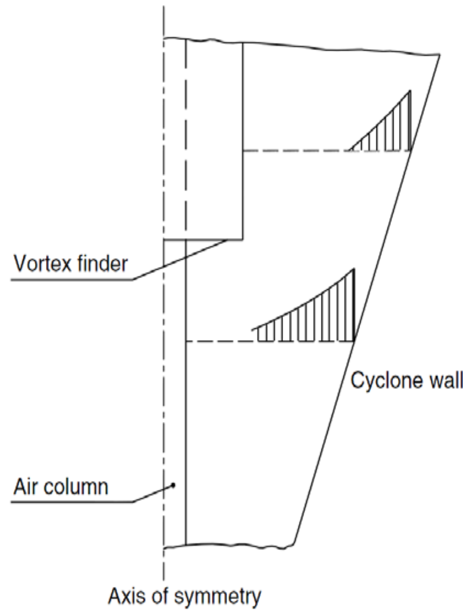
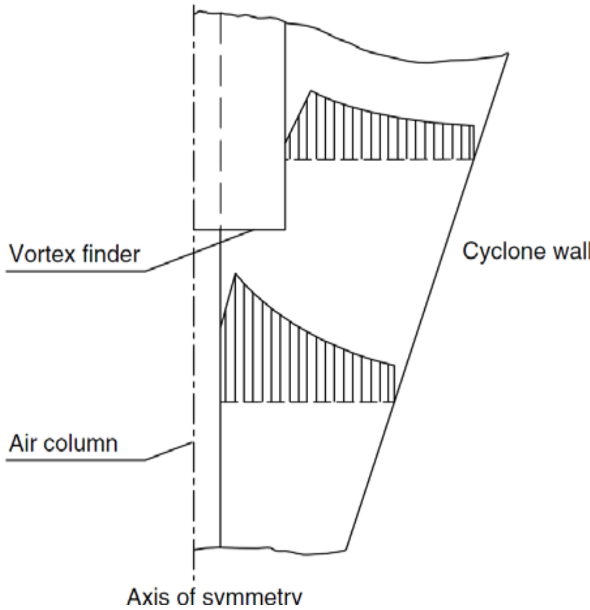
Velocity distribution inside the Cyclone



Axial velocity



Radial velocity



Tangential velocity

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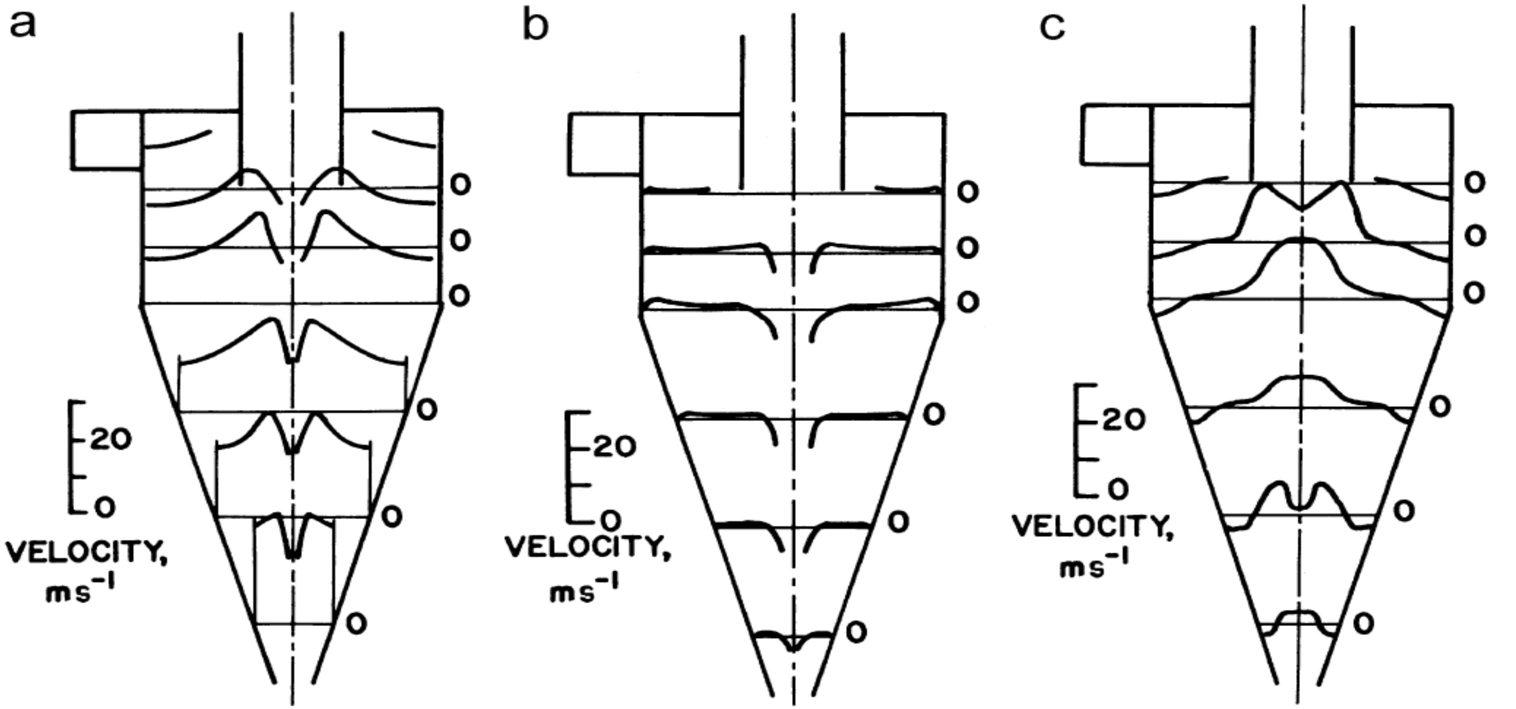
Velocity distribution inside the Cyclone



Axial velocity Radial velocity Tangential velocity

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Cyclone Design;

Two type of cyclones are designed as standard gas-solid cyclone separators

High efficiency cyclone (Figure 1a)

High flowrate cyclone (Figure 1b)

The two type of cyclones should be designed to give an inlet velocity of between 9 and 27 m/s (30 to 90 ft/s); the optimum inlet velocity has been found to be 15 m/s (50 ft/s).

The performance curves for these designs, obtained experimentally under standard test conditions, are shown in Figures 2a and 2b. These curves can be transformed to other cyclone sizes and operating conditions by use of the following scaling equation, for a given separating efficiency:

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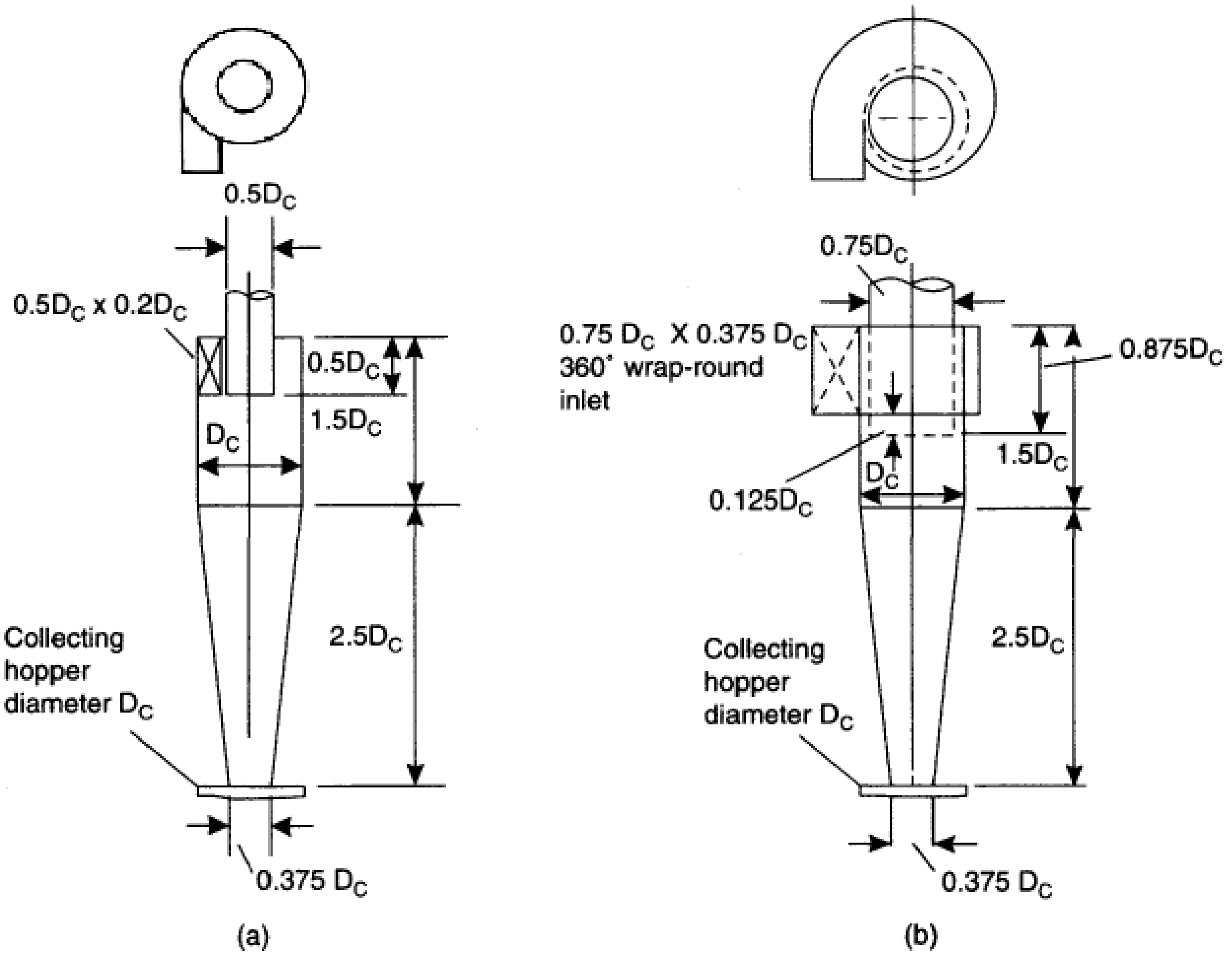

Figure 1. Standard cyclone dimension *(a)* High efficiency cyclone *(b)* High gas rate cyclone

Cyclone separator

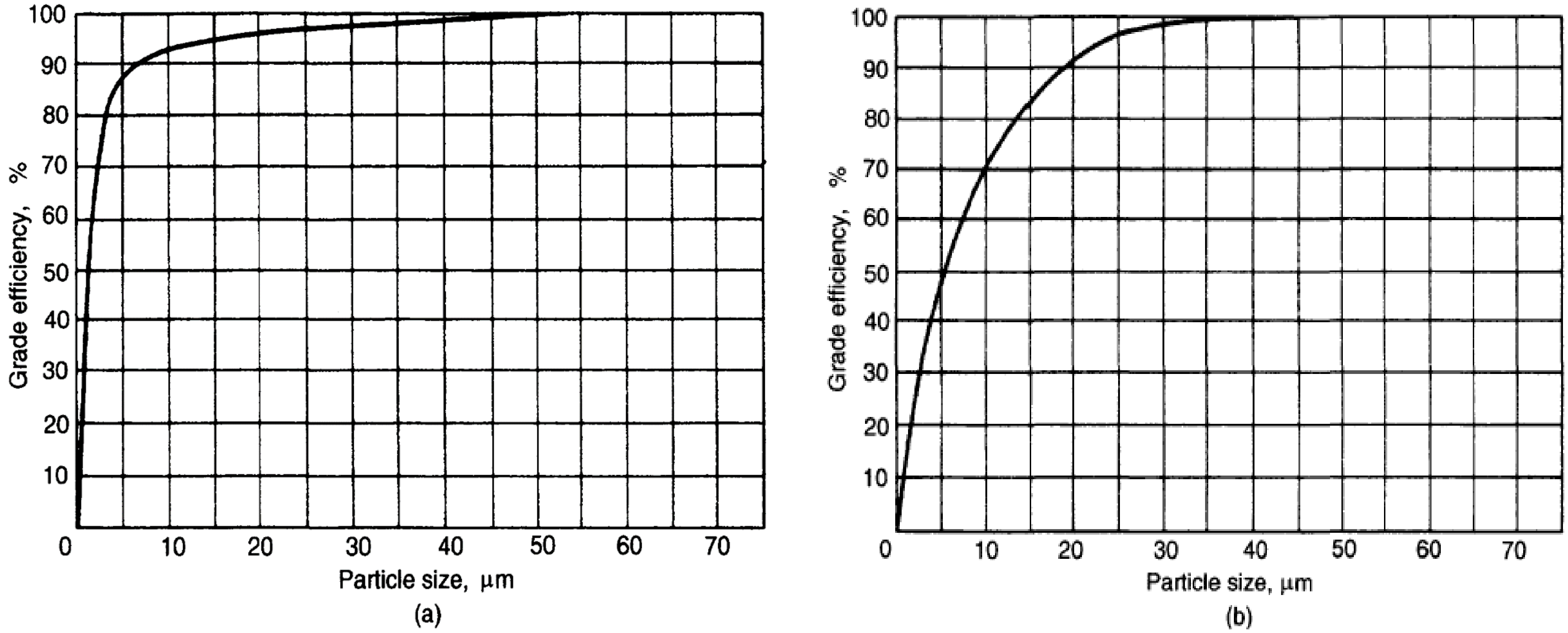

Figure 2. Performance curves, standard conditions*(a)* High efficiency cyclone *(b)* High gas rate cyclone

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The above curves can be transformed to other cyclone sizes and operating conditions by use of the following scaling equation, for a given separating efficiency:

$$\frac{d_2}{d1} = \sqrt{\left(\frac{D_{c2}}{D_{c1}}\right)^3 \frac{Q_1}{Q_2} \frac{\Delta\rho_1}{\Delta\rho_2} \frac{\mu_2}{\mu_1}}$$

Where;

d1= mean diameter of particle separated at the standard conditions, at the chosen separating efficiency, from Figures 3a or 3b.

d2 = mean diameter of the particle separated in the proposed design, at the same separating efficiency,

D_{C1} = diameter of the standard cyclone = 8 inches (203 mm),

D_{C2} = diameter of proposed cyclone, mm,

Q1=standard flow rate (for high efficiency design Q1 = 223 m^3/h, for high throughput design Q1= 669 m^3/h,

Q2 = proposed flow rate, m^3/h,

$\Delta\rho 1$ = solid-fluid density difference in standard conditions = 2000 kg/m^3,

$\Delta\rho 2$ =density difference, proposed design,

$\mu 1$= test fluid viscosity (air at 1 atm, 20°C) = 0.018 mN s/m^2,

$\mu 2$= viscosity, proposed fluid (mN s/m^2)

Cyclone separator

Pressure drop; The pressure drop in a cyclone will be due to the entry and exit losses, and friction and kinetic energy losses in the cyclone. The empirical equation given by Stairmand (1949) can be used to estimate the pressure drop:

$$\Delta P = \frac{\rho_f}{203}\left[u_1^2 \left(1 + 2\phi^2 \left(\frac{2r_1}{r_e} - 1 \right) \right) + 2u_2^2 \right]$$

Where:

ΔP = cyclone pressure drop, millibars,
ρ_f = gas density, kg/m^3,

u_1 = inlet duct velocity, m/s,
u_2 = exit duct velocity, m/s,
r_t = radius of circle to which the centre line of the inlet is tangential, m,
r_e = radius of exit pipe, m,

Cyclone separator

ϕ= factor specified from Figure 4

ψ= parameter demonstrated from Figure 4 and given by equation below;

$$\psi = f_c \frac{A_s}{A_1}$$

fc =friction factor, taken as 0.005 for gases,

As = surface area of cyclone exposed to the spinning fluid, m^2.

For design purposes this can be taken as equal to the surface area of a cylinder with the same diameter as the cyclone and length equal to the total height of the cyclone (barrel plus cone).

A1=area of inlet duct, m^2.

Cyclone separator

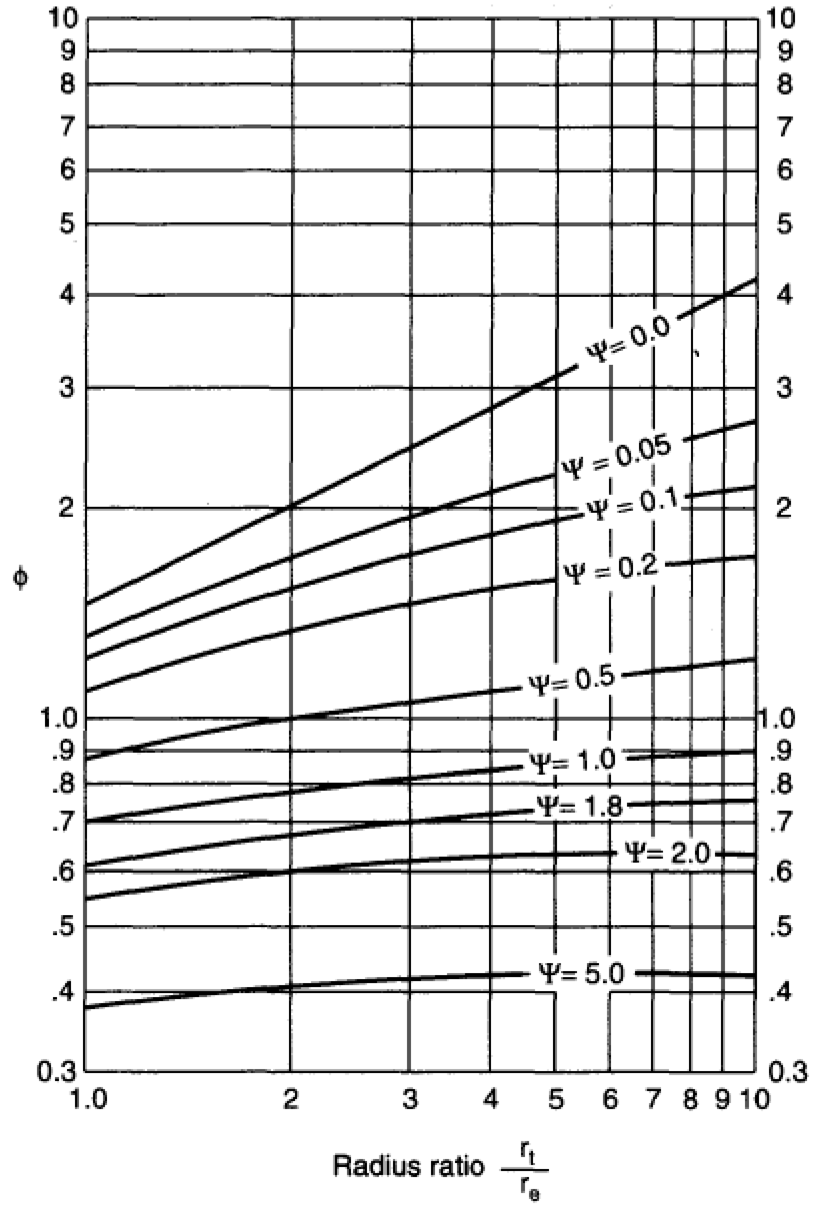

Figure 3. Cyclone pressure drop factor

Cyclone separator

Design procedure:

1. Select either the high-efficiency or high-throughput design, depending on the performance required.
2. Obtain an estimate of the particle size distribution of the solids in the stream to be treated.
3. Estimate the number of cyclones needed in parallel.
4. Calculate the cyclone diameter for an inlet velocity of 15 m/s (50 ft/s). Scale the other cyclone dimensions from Figures 1a or 1b.
5. Calculate the scale-up factor for the transposition of Figures 2a or 2b.
6. Calculate the cyclone performance and overall efficiency (**recovery of solids**). If unsatisfactory try a smaller diameter.
7. Calculate the cyclone pressure drop using Figure 3 and if required, select a suitable blower.
8. Calculate the efficiency of collection and cyclone performance

CYCLONE SEPARATOR

Design Problem

It desired to design cyclone separator to recover solids from air stream with volumetric flow-rate of 5000 m3/h at atmospheric pressure and temperature of 100°C. Screen analysis of the solid particle size distribution to be removed is given below with estimated density of the solid particles as 2800 kg/m^3.

***Assume* 85 per cent recovery of the solids is required for design.**

Particle size (µm)	**Weight Fraction**
60-50	6
50-40	8
40-30	12
30-20	17
20-10	25
10-5	25
5-2	5
2-0	2

Cyclone separator

Physical Properties of air - temperatures ranging -150 oC to 400 oC

Temperature - *t* - (^oC)	Density - ρ - (kg/m^3)	Specific Heat - c_p - ($kJ/(kg\ K)$)	Thermal Conductivity - *k* - ($W/(m\ K)$)	Kinematic Viscosity - ν - $x\ 10^{-6}\ (m^2/s)$	Expansion Coefficient - *b* - $x\ 10^{-3}\ (1/K)$	Prandtl's Number - P_r -
-150	2.793	1.026	0.0116	3.08	8.21	0.76
-100	1.980	1.009	0.0160	5.95	5.82	0.74
-50	1.534	1.005	0.0204	9.55	4.51	0.725
0	1.293	1.005	0.0243	13.30	3.67	0.715
20	1.205	1.005	0.0257	15.11	3.43	0.713
40	1.127	1.005	0.0271	16.97	3.20	0.711
60	1.067	1.009	0.0285	18.90	3.00	0.709
80	1.000	1.009	0.0299	20.94	2.83	0.708
100	**0.946**	**1.009**	**0.0314**	**23.06**	**2.68**	**0.703**
120	0.898	1.013	0.0328	25.23	2.55	0.70
140	0.854	1.013	0.0343	27.55	2.43	0.695
160	0.815	1.017	0.0358	29.85	2.32	0.69
180	0.779	1.022	0.0372	32.29	2.21	0.69
200	0.746	1.026	0.0386	34.63	2.11	0.685
250	0.675	1.034	0.0421	41.17	1.91	0.68
300	0.616	1.047	0.0454	47.85	1.75	0.68
350	0.566	1.055	0.0485	55.05	1.61	0.68
400	0.524	1.068	0.0515	62.53	1.49	0.68

Cyclone separator

Solution

As 25 per cent of the particles are below 10 μm the high-efficiency design will be required to give the specified recovery.

Flowrate = 5000/3600 = 1.389 m^3/s

Area of inlet duct at 15 m/s = 1.389/15 = 0.0926 m^2

Area of inlet duct= 0.5Dc x 0.2 Dc = 0.0926 m^2

Dc = 0.962 m

This is clearly too large as compared with the standard design diameter of 8 inch (0.203 m). Try four cyclones in parallel, D_c = 0.481 m

Physical properties of air at 100 C (from Table)

Density of air at 100 C = 0.946 kg/m^3

Dynamic viscosity of air at 100 C = 0.946 x 23.06 x E-6

= 0.0218 cp (mN s/m^2)

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Flowrate per cyclone = 5000/4 =1250 m^3/h
From Equation below find scaling factor

$$\frac{d_2}{d1} = \sqrt{(\frac{D_{c2}}{D_{c1}})^3 \ \frac{Q_1}{Q_2} \ \frac{\Delta\rho_1}{\Delta\rho_2} \ \frac{\mu_2}{\mu_1}}$$

$$\text{Scaling Factor} \ = \sqrt{(\frac{0.481}{0.203})^3 \times \frac{233}{1250} \times \frac{2000}{2800} \times \frac{0.0218}{0.018}}$$

= 1.465

1.4328

Negligible gas density compared with the solids particle density

Cyclone separator

The performance calculations, using this scaling factor and Figure 10.45a, are set out in the table below:

Particle size (µm)	**Weight Fraction**	**Mean Particle size (µm)**	**Efficiency at scaled size % (from Fig. 2a)**	**Collection Efficiency %**	**Grading at exit**	**Percentage at exit**
60-50	6	37.5	98	5.88	0.12	1.17
50-40	8	30.7	97	7.76	0.26	2.54
40-30	12	23.89	96	11.56	0.44	4.31
30-20	17	17	95	16.15	0.85	8.31
20-10	25	10.24	93	23.25	1.75	17.13
10-5	25	5.12	88	22	3	29.35
5-2	5	2.39	60	3	2	19.57
2-0	2	0.68	10	0.2	1.8	17.62
	100			**89.8**	**10.22**	**100**

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Pressure drop calculation

$$\Delta P = \frac{\rho_f}{203}\left[u_1^2\left(1+2\phi^2\left(\frac{2r_1}{r_e}-1\right)\right)+2u_2^2\right]$$

Area of inlet duct A1= 0.0231m2

Cyclone surface area As = π x 0.481x (4 x 0.481) = 2.91m^2

f c taken as 0.005

$$\psi = f_c\,\frac{A_s}{A_1} = 0.005\times\frac{2.91}{0.3367} = 0.628$$

$$\frac{r_1}{r_e} = \frac{0.481-\left(\frac{0.2*0.481}{2}\right)}{0.25*0.481} = 3.6$$

From Fig.3, ϕ = 1

Cyclone separator

$$u_1 = \frac{1250}{3600 \times 0.0231} = 15 m/s$$

$$\text{Area of exit pipe} = \frac{\pi(0.5 \times 0.481)^2}{4} = 0.045 m^2$$

$$u_2 = \frac{1250}{3600 \times 0.045} = 7.71 m/s$$

$$\Delta P = \frac{0.946}{203}\left[15^2\left(1 + 2 \times 1^2\left(2 \times 1.6 - 1\right)\right) + 2 \times 7.71^2\right] = 5.94 mbar$$

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Collection Efficiency; A very simple model can be used to determine the effects of both cyclone design and operation on collection efficiency. In this model, gas spins through a number N of revolutions in the outer vortex. The value of N can be approximated as the sum of revolutions inside the body and inside the cone:

$$N = \frac{1}{H}\left(L_b + \frac{L_c}{2} \right)$$

where

N = number of turns inside the device (no units)

H = height of inlet duct (m or ft)

L_b = length of cyclone body (m or ft)

L_c = length (vertical) of cyclone cone (m or ft).

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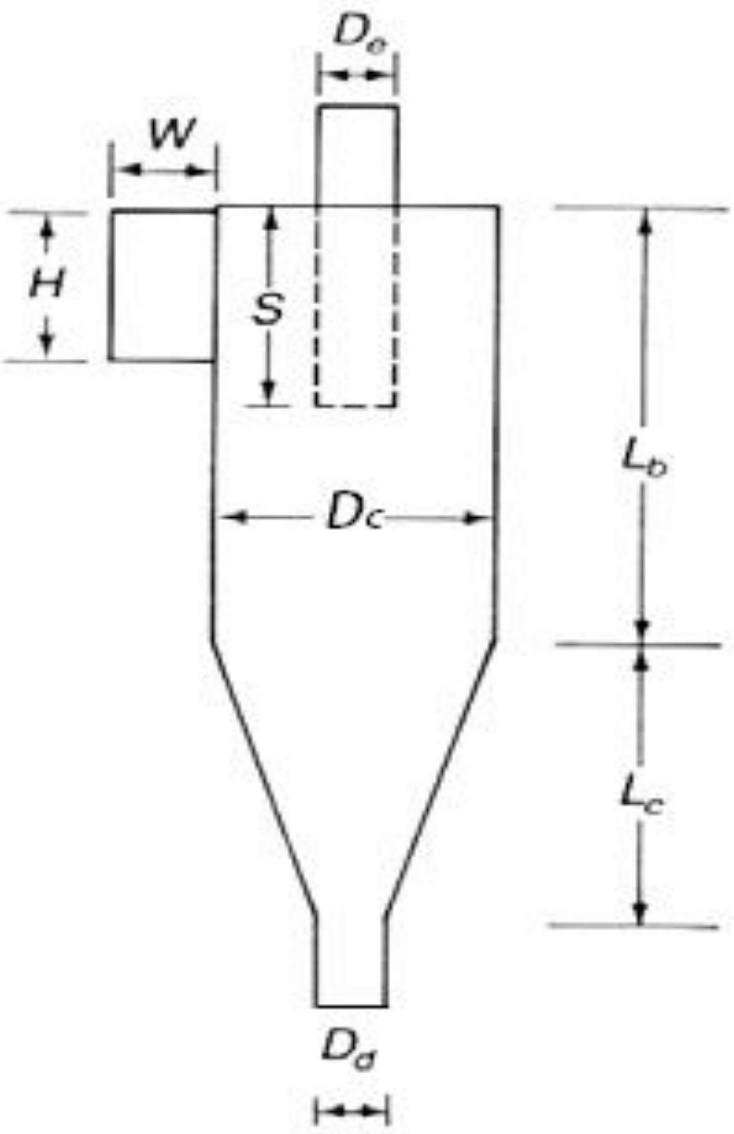
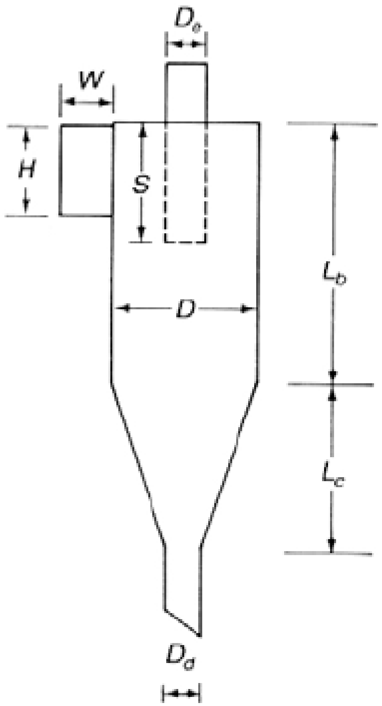


Cyclone separator

Standard cyclone dimensions

	Cyclone Type					
	High Efficiency		Conventional		High Throughput	
	(1)	(2)	(3)	(4)	(5)	(6)
Body Diameter, D/D	1.0	1.0	1.0	1.0	1.0	1.0
Height of Inlet, H/D	0.5	0.44	0.5	0.5	0.75	0.8
Width of Inlet, W/D	0.2	0.21	0.25	0.25	0.375	0.35
Diameter of Gas Exit, D_e/D	0.5	0.4	0.5	0.5	0.75	0.75
Length of Vortex Finder, S/D	0.5	0.5	0.625	0.6	0.875	0.85
Length of Body, L_b/D	1.5	1.4	2.0	1.75	1.5	1.7
Length of Cone, L_c/D	2.5	2.5	2.0	2.0	2.5	2.0
Diameter of Dust Outlet, D_d/D	0.375	0.4	0.25	0.4	0.375	0.4



SOURCES:
Columns (1) and (5) = Stairmand, 1951; columns (2), (4) and (6) = Swift, 1969; column (3) and sketch = Lapple, 1951.

Cyclone separator

To be collected, particles must strike the wall within the amount of time that the gas travels in the outer vortex. The gas residence time in the outer vortex is

$$\Delta t = \frac{path\,length}{Speed} = \frac{\pi D N}{v_i}$$

where

Δt = time spent by gas during spiraling descent (sec)

D = cyclone body diameter (m or ft)

v_i = gas inlet velocity (m/s or ft/s) = Q/wH

Q = volumetric inflow (m^3/s or ft^3/s)

H = height of inlet (m or ft)

w = width of inlet (m or ft).

Cyclone separator

The maximum radial distance traveled by any particle is the width of the inlet duct W. The centrifugal force quickly accelerates the particle to its terminal velocity in the outward (radial) direction, with the opposing drag force equaling the centrifugal force. The terminal velocity that will just allow a particle initially at distance *w* away from the wall to be collected in time is;

$$V_t = \frac{w}{\Delta t}$$

where

V_t = particle drift velocity in the radial direction (m/s or ft/s).

Cyclone separator

The particle drift velocity is a function of particle size. Assuming Stokes regime flow (drag force = $3\pi\mu d_p V_t$) and spherical particles subjected to a centrifugal force mv^2/r, with m = mass of particle in excess of mass of air displaced, $v = V_i$ of inlet flow, and $r = D/2$, we obtain

$$V_t = \frac{(\rho_p - \rho_a)\, d_p^2 V_i^2}{9\mu D}$$

where

V_t = terminal drift transverse velocity (m/s or ft/s)

d_p = diameter of the particle (m or ft)

ρ_p= density of the particle (kg/m^3)

ρ_a = air density (kg/m^3)

μ = air viscosity (kg/m.s).

Cyclone separator

Substitution of the 2nd equation into the 3rd eliminates Δt. Then, setting the two expressions for *Vt* equal to each other and rearranging to solve for particle diameter, we obtain

$$d_p = \left[\frac{9\mu w}{\pi N V_i \left(\rho_p - \rho_a \right)_i} \right]^{0.5}$$

It is worth noting that in this expression, dp is the size of the smallest particle that will be collected if it starts at the inside edge of the inlet duct. Thus, in theory, all particles of size dp or larger should be collected with 100% efficiency. Note that the units must be consistent in all equations. One consistent set is m for *dp*, *r* and *w*; m/s for *Vi* and *Vt*; kg/m.s for μ; and kg/m^3 for ρp and ρa. An equivalent set in English units is ft for *dp*, *r* and *w*; ft/sec for *Vi* and *Vt*; lbm/ft.sec for μ; and lbm/ft^3 for for ρp and ρa.

Cyclone separator

The efficiency of collection of any size of particle is given by;

$$\eta_j = \frac{1}{1 + \left(d_{pc} / d_{pj} \right)^2}$$

η_j= collection efficiency of particles in the jth size range ($0 < \eta_j < 1$)

d_{pj} = characteristic diameter of the jth particle size range (in µm).

Cyclone separator

The overall efficiency, called performance, of the cyclone is a weighted average of the collection efficiencies for the various size ranges, namely

$$\eta = \frac{\sum \eta_j m_j}{M}$$

where

η = overall collection efficiency ($0 < \eta_j < 1$)

m_j = mass of particles in the jth size range

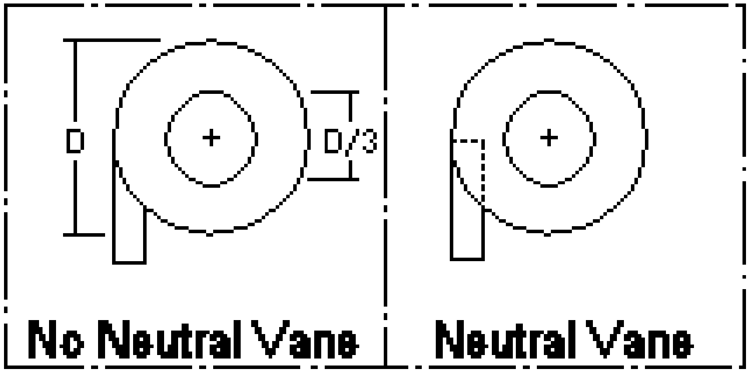
M = total mass of particles.

CYCLONE SEPARATOR

Pressure drop; The pressure drop in a cyclone will be due to the entry and exit losses, and friction and kinetic energy losses in the cyclone. Correlations for pressure drop have value and acceptable up to 10 in H_2O.

$$\Delta P = 0.5\rho_g v_i^2 N_H$$

$$N_H = K\left(\frac{wH}{D_e^2}\right)$$



ΔP = Pressure drop, Pascal

v_i = Inlet velocity (m/s).

ρ_f = Fluid density (kg/m^3).

N_H = Number of inlet velocity heads.

K = a constant depend on cyclone configuration and operating condition and its value used as K=16 for no inlet vane and K=7.5 with neutral inlet vane.

H = Height of inlet (m).

w = Width of inlet (m).

Common ranges for pressure drops:

Low efficiency cyclone	2-4 inches of water (500 – 1000 Pa)
Medium efficiency cyclone	4-8 inches of water (1000 – 2000 Pa)
High efficiency cyclone	8-10 inches of water (2000 – 2500 Pa)

Power required ; is calculated as energy per unit volume gas multiplied by volume of gas inlet per unit time.

$$P = \Delta P \times Q$$

ΔP = Pressure drop, Pascal

Q = *volume rate* m^3/s

P = Power required watt

Cyclone separator

The preceding equation shows that, in theory, the smallest diameter of particles collected with 100% efficiency is directly related to gas viscosity and inlet duct width, and inversely related to the number of effective turns, inlet gas velocity, and density difference between the particles and the gas. In practice, collection efficiency does, in fact, depend on these parameters. However, the model has a major flaw: It predicts that all particles larger than dp will be collected with 100% efficiency, which is incorrect. This discrepancy is the result of all our approximations. ***Lapple*** (1951) developed a semi-empirical relationship to calculate a "50% cut diameter" d_{pc}, which is the diameter of particles collected with 50% efficiency. The expression is;

$$d_{pc} = \left[\frac{9\mu w}{2\pi N V_i \left(\rho_p - \rho_a \right)_i} \right]^{0.5}$$

where d_{pc} = diameter of particle collected with 50% efficiency.

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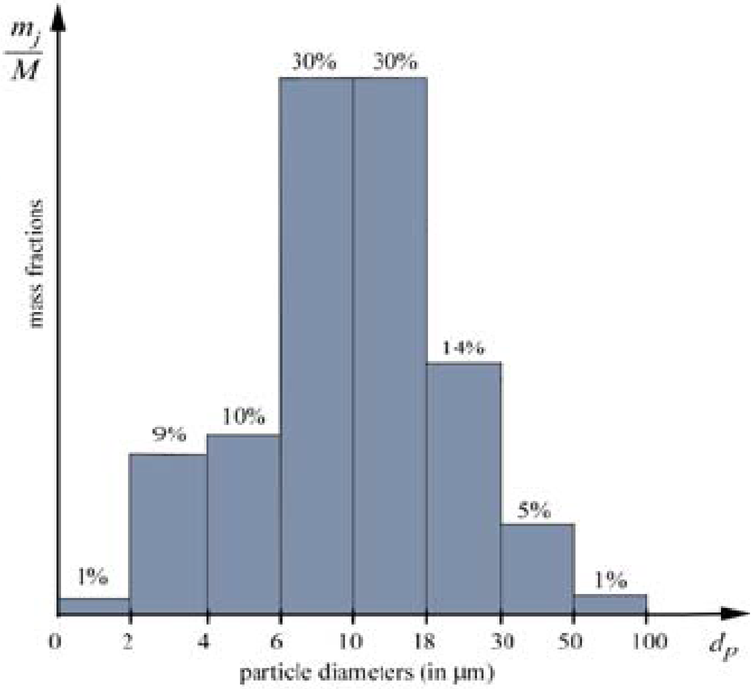
Example of Cyclone Analysis

Given:

Conventional type (standard proportions)
D = 1.0 m
Flow rate = Q = 150 m³/min
Particle density = ρ_p = 1600 kg/m³
Particle size distribution as follows:

Particle size (d_p)	% mass in that size (m/M)
0-2 μm	1.0%
2-4 μm	9.0%
4-6 μm	10.0%
6-10 μm	30.0%
10-18 μm	30.0%
18-30 μm	14.0%
30-50 μm	5.0%
50-100 μm	1.0%
	100%



Question:

What is the collection efficiency?

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Solution

$$N = \frac{1}{H}\left(L_b + \frac{L_c}{2}\right) = 6 \qquad V_i = \frac{Q}{WH} = \frac{Q}{0.125\,D^2} = 1200 \text{ m/min} = 20 \text{ m/s}$$

$$d_{pc} = \sqrt{\frac{9}{2\pi}\frac{\mu W}{NV_i(\rho_p - \rho_a)}} = \sqrt{\frac{9}{2\pi}\frac{0.25\,\mu D}{6V_i(\rho_p - \rho_a)}} = 5.79 \times 10^{-6}\,\text{m} = 5.79\ \mu\text{m}$$

Size range (in μm)	Average size d_p (in μm)	Collection efficiency η	Mass fraction m/M	Contribution to performance $\eta \times m/M$
0 – 2	1	2.9%	0.01	0.029%
2 – 4	3	21.1%	0.09	1.903%
4 – 6	5	42.7%	0.10	4.268%
6 – 10	8	65.6%	0.30	19.678%
10 – 18	14	85.4%	0.30	25.613%
18 – 30	24	94.5%	0.14	11.953%
30 – 50	40	97.9%	0.05	4.897%
50 - 100	75	99.4%	0.01	0.994%
			1.00	70.6%